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13. ABSTRACT *(Maximum 200 words)*

Specialized tools have been developed to elucidate the fundamental mechanisms driving the interaction between delamination crack tip conditions and local and global buckling modes in two dimensional problems of compressively loaded composite flat panels and cylindrical shells. Significant progress was made in understanding the interplay between the energy going into the fracture process and the structural deformation modes.

For flat composite panels subjected to compressive loadings, it was found that when a delamination was above a critical length, the postbuckling behavior shifted from stable to unstable. The bifurcation eigenvectors for the composit panels have been analyzed and it was determined that they are orthogonal for cases with a stable postbuckling path and nonorthogonal (coupled) when the postbuckling load-deflection response is unstable. It thus appears that the local energy associated with a delamination crack tip provides a mechanism for coupling the local and global buckling modes of the panel when the structural flexibilities are in a critical region.

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Introduction

Under grantN000149410785, Dynamic Failure Modes for Fluid Pressure Loaded Composite Shells, with the Office of Naval Research, specialized tools have been developed to elucidate the fundamental mechanisms driving the interaction between delamination crack tip conditions and local and global buckling modes in two dimensional problems of compressively loaded composite flat panels and cylindrical shells. Significant progress was made in understanding the interplay between the energy going into the fracture process and the structural deformation modes.

Our recent work has demonstrated that the bifurcation buckling eigenvectors provide significant insight into the origins of modal interactions. For structures which do not exhibit the drastic imperfection sensitivity characteristic of mode coupling, the bifurcation eigenvectors from finite element simulations, when interpreted as piecewise continuous functions over the shell geometry, are orthogonal. We have observed that the eigenvectors are not orthogonal functions for geometries which appear to demonstrate mode coupling. For flat composite panels subjected to compressive loadings, it was found that when a delamination was above a critical length, the postbuckling behavior shifted from stable to unstable. Recently, we have analyzed the bifurcation eigenvectors for the composite panels and determined that they are orthogonal for cases with a stable postbuckling path and nonorthogonal (coupled) when the postbuckling load-deflection response is unstable. It thus appears that the local energy associated with a delamination crack tip provides a mechanism for coupling the local and global buckling modes of the panel when the structural flexibilities are in a critical region.

Summary of Accomplishments

In composite structures, delamination growth is a critical failure mode at both the material and the structural level. In Figure 1 below, which is taken from ref. 1, the geometry of our two dimensional flat panel study is shown. Under compressive loading for certain levels of initial delamination length, the panel eventually reaches a deformation state as shown in Figure 2. The deformation in Figure 2 can be characterized as consisting of a combination of overall (global) panel buckling, local (ligament) buckling, and a mixed mode (modes I and II) crack opening.

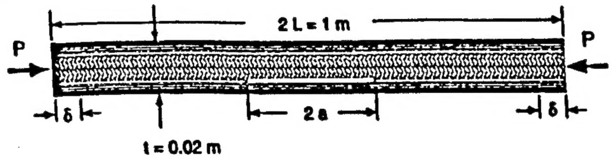


Figure 1. Geometry of panel modeled

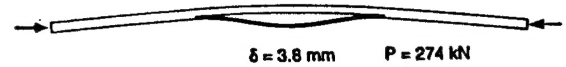
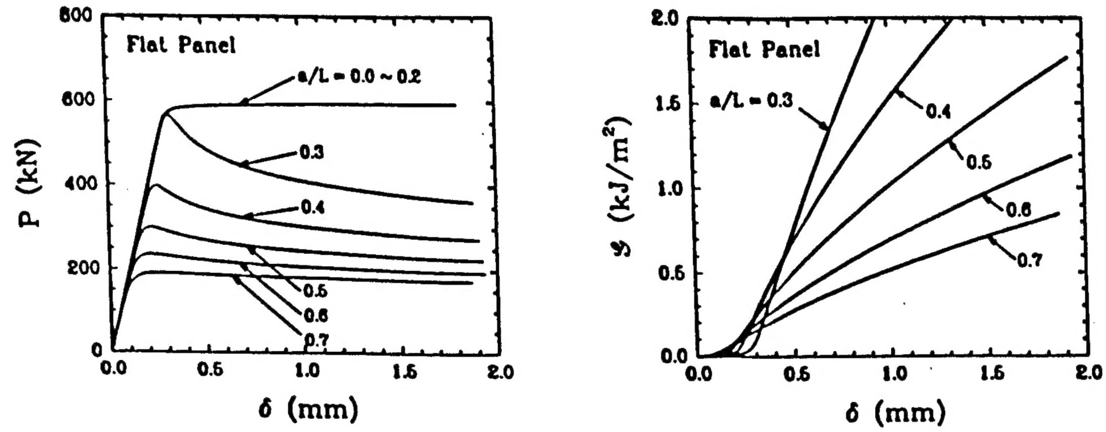


Figure 2. Combined mode deformation (a/L=0.4)

The load and energy release rate are shown as functions of end-shortening in Figures 3 for various size delaminations. It has been found that for the geometry and ply lay-up considered, if a/L is less than 0.23, the crack never opens up and only the global buckling mode is found to exist. For larger delamination lengths, the cracks open and a deformation shape such as that shown in Figure 2 is found. For these cases, the initial postbuckling behavior is seen to be unstable and characteristic



(a) End load (b) Energy release rate

Figure 3. Responses of panel with delamination shown as functions of end-shortening.

of an imperfection sensitive structure. From a structural reliability perspective, the types of behavior implied by the responses shown in Figure 3(a) and (b) are very significant. If we consider the cases of a/L equal to 0.3 and 0.4, we observe that a sharp drop in load occurs at the inception of buckling. Also at this point, the energy release rate goes from almost zero to levels associated with the material toughness at a very rapid rate. In this geometry regime, the delamination ligament remains closed and compressed along with the rest of the panel until the buckling load of the ligament is reached. At this point the ligament buckles outward causing a large crack tip energy and a local stress state which produced a bending moment which initiates the global buckling of the panel. In order to avoid such catastrophic failure modes in composite structures, it is desirable to have tools which are capable of identifying whether a structural design is likely to exhibit such highly coupled, catastrophic failure modes.

Eigenvector Orthogonality for a/L=0				
	1	2	3	4
1	1.0000	0.00244	0.0097	0.0206
2	0.00244	1.0000	-0.0020	-0.0048
3	0.0097	-0.0020	1.0000	-0.0011
4	0.0206	-0.0048	-0.0011	1.0000

Eigenvector Orthogonality for a/L=0.3				
	1	2	3	4
1	1.0000	-0.7963	0.0632	-0.2767
2	-0.7963	1.0000	-0.0458	0.5011
3	0.0632	-0.0458	1.0000	-0.6672
4	-0.2767	0.5011	-0.6672	1.0000

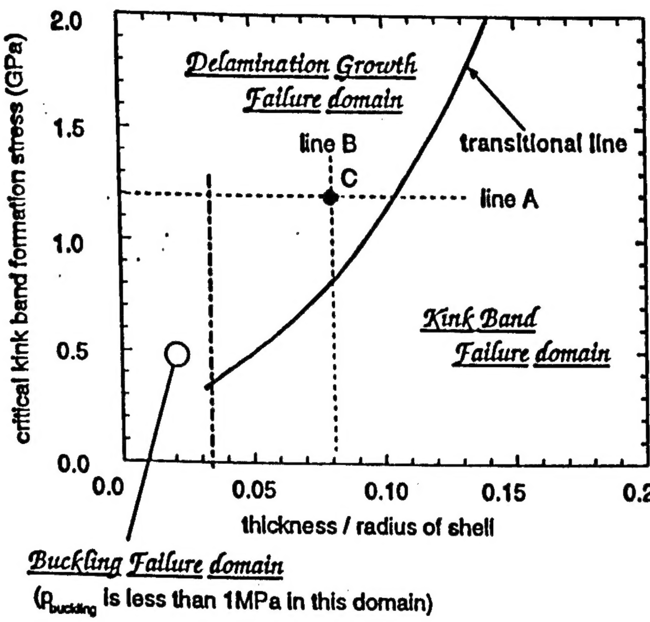
Eigenvector Orthogonality for a/L=0.4				
	1	2	3	4
1	1.0000	0.8626	0.0956	-0.1168
2	0.8626	1.0000	0.3430	-0.0912
3	0.0956	0.3430	1.0000	0.7058
4	-0.1168	-0.0912	0.7058	1.0000

(a) a/L = 0 (b) a/L = 0.3 (b) a/L = 0.4

Figure 4. Eigenvector inner products for panel with different delamination lengths

In studying the failure characteristics of stiffened shell structures under hydrostatic loadings, Kushner (ref. 2) has identified the orthogonality of the bifurcation eigenvectors as an indicator of buckling mode coupling. This work has helped identify the reasons for the apparently anomalous behavior obtained in an extensive UNDEX test program on small models at the Carderock Division of NSWC. In Figure 4 we show the eigenvector inner products for the cases of a/L equal to 0.0, 0.3 and 0.4. Recall that in Figure 3(a) it was seen that the first case had a stable postbuckled path, while the second and third cases had unstable postbuckled paths. Figure 4 shows that the transition from stable to unstable postbuckling behavior is associated with a change in characteristic of the bifurcation eigenvectors from orthogonal to nonorthogonal.

While our research has concentrated on delineating the mechanisms associatiated with the buckling/delamination growth coupling, significant recent research results have been published (reference 5) which help explain the initiation and propagation of kink bands as a failure mechanism in compressively loaded composite laminates. We have incorporated the analytical results of Liu and Shih (reference 5) togehter with our own results to create a plot which can be used to define the critical failure mode for a structure as a function of geometry, mechanical properties and applied load. An example is shown in Figure 5 below for the case of a four layer, [0/90/90/0] cylinder with r = 0.2m, $\mathcal{G}_c = 0.72$ kJ/m^2, and initial delmination angle, Θ =5°.



Procedure to determine the failure mode:

1. Set critical compressive kink band stress, e.g., 1.2 GPa, (*line A*)
2. Choose appropriate thickness for shell, e.g., 16mm or t/R = 0.8 (*line B*)
3. Mark intersection and determine failure mode (*point C, Delamination Growth*)

Figure 5. Design Diagram to Determine Failure Modes

We have also recently begun to investigate the behavior of 3-D rectangular plates and finite length cylindrical shells containing initial delaminations in the shape of penny shaped cracks. In order to keep the computational size of the problem to a solvable level, computational models which blend continuum and shell finite elements will be utilized. A simple example of this

approach is shown in Figure 6. A three dimensional formulation of the interface fracture procedure

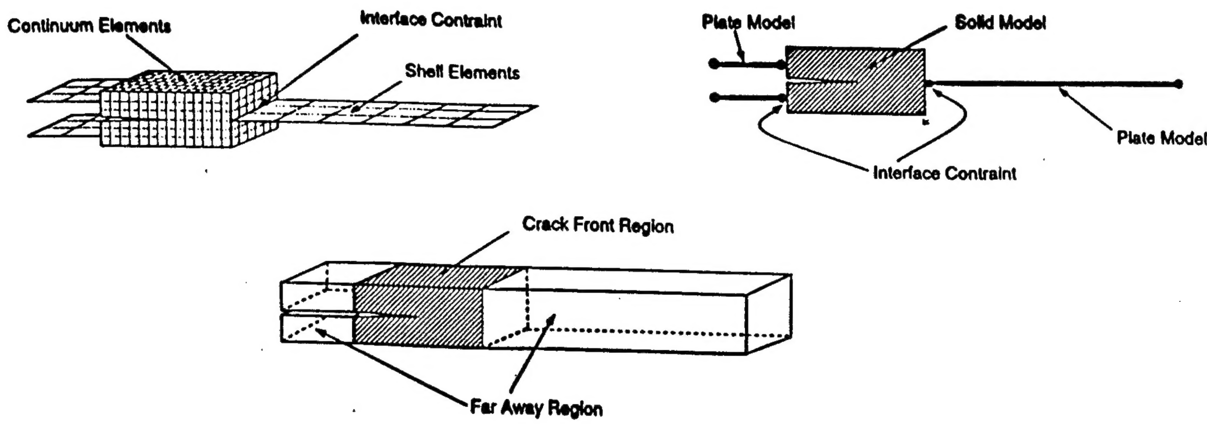


Figure 6. Three-dimensional computational modeling strategy

developed in our previous ONR grant will be implemented to allow for the computation of non-selfsimilar crack growth due to loading asymmetry and ply stacking sequence. Initial studies have shown consistency of the three dimensional models using combined shell/continuum models when compared to all continuum models. Figure 7 shows a comparison of predictions of the first buckling mode for the thick (L/t = 10) panel with an initial delamination equal to 30% of the length. The result from the 2-D plane strain model discussed earlier is shown in Figure 7(a). Figure 7(b) shows results from a model using 3-D elements constrained to plane strain conditions at the front and rear faces and Figure 7(c) shows the results when 3-D elements away from the delamination region are replaced with shell elements. As can be seen, the three models show very good agreement in both the shape of the eigenvector and the critical buckling load. The slight increase in critical load for the model using both continuum and shell elements can be shown to be caused by the overly stiff transverse shear behavior of the shell elements for this relatively thick geometry. Comparisons for higher buckling eigenmodes show similar levels of agreement with the degree of error in buckling pressure for the models using shell elements depending on the amount of bending in the regions removed from the delamination. In our previous work, we

$P_c = 574.0$ (a) 2-D Plane Strain

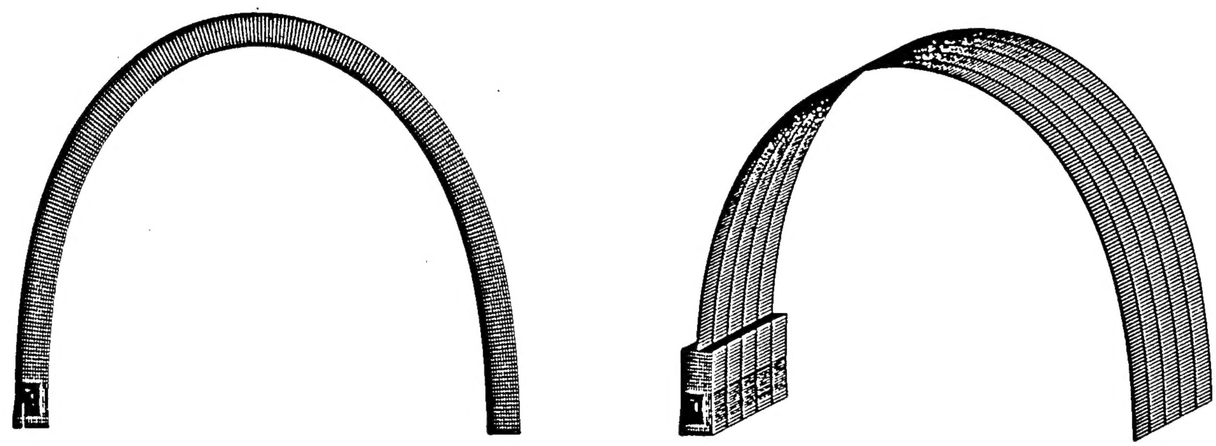
$P_c = 575.7$ (b) 3-D Continuum

$P_c = 582.9$ (c) Combined 3-D Continuum & Shell

Figure 7. Various modeling comparisons for panel with (a/L = 0.3)

considered not only flat panels, but also cylindrical shells. For the three dimensional studies proposed, the cylindrical shell problems add an additional level of complexity to the problem. In

two dimensions, uncracked panels and cylinders both have stable postbuckling behavior. For the three dimensional case, a cylinder under hydrostatic loading has an unstable postbuckling behavior. Under such conditions, a destabilizing delamination could lead to severe imperfection sensitivity and highly unstable collapse processes. We have completed an initial 3-D modeling using a technique similar to that used for the panel and the results are shown in Figure 8. The p_c values shown correspond to the computed critical buckling pressure associated with each model.



$p_c = 19.9$

(a) 2-D Plane Strain

$p_c = 21.4$

(b) Combined 3-D Continuum and Shell

Figure 8. Half-models of externally pressurized cylindrical shell with delamination

We note that computational time for a combined 3-D continuum and shell element model is less than 50% of time required for an equivalent full 3-D continuum model. In addition, we have successfully modeled a penny shaped delamination in a flat panel as shown in Figure 9.

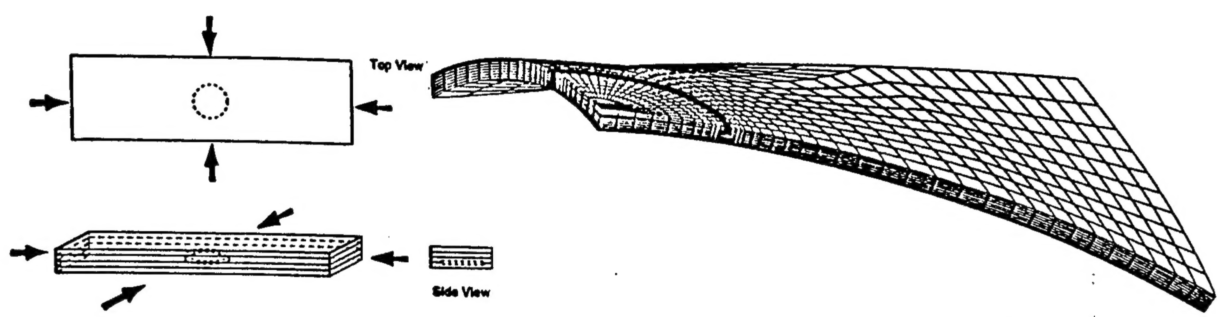


Figure 9. Model for penny-shaped delamination in biaxially loaded panel

Graduate Students Supported

Dr. Ramesh Gopalakrishnan and Dr. C.Y. Lo both produced Ph.D. theses under the support of this grant. Mr. L.C. Wu completed a Master's thesis with support from this grant

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